Design and Optimization of Coal Plants of the Future

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Gasification Systems, and Transformative Power Generation
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Outline

- Why do this?
    - Getting from existing fleet to next-generation

- What are the objectives?
    - Desired characteristics for the next-generation of coal plants
    - Status quo of existing PSE tools to solve this problem

- How do we solve the problem?
    - The need for advanced modeling and optimization tools
    - How the IDAES project fits here?

Why do this?

- Fossil Energy Objectives
  - Cost of Energy and CO_2 Capture from Advanced Power Systems – Develop cost-effective, efficient, and reliable CO_2 separation technologies and energy conversion technologies that inherently capture CO_2, for both new and existing coal-fired power plants.
  - Power Plant Efficiency Improvements – Develop cost-effective, reliable technologies to improve the efficiency of new and existing coal-fired power plants.

What should be the characteristics of the next-generation of coal plants to provide secure, stable, and reliable power?

IDAES
Institute for the Design of Advanced Energy Systems

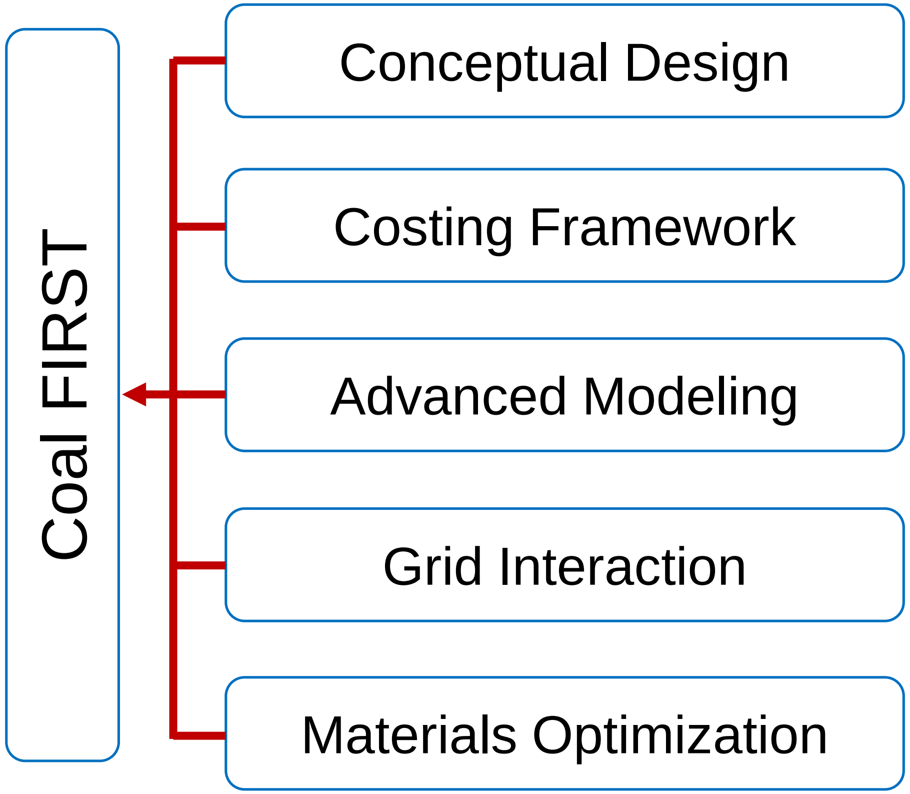
What are the desired characteristics?

- Flexible operations to meet the needs of the modern grid
  - High ramp rates and minimum load operation (renewable targets 2050)
- Innovative solutions to improve efficiency and reduce emissions
  - > 40% HHV efficiency, near zero emissions, low water consumption
- Resilient capability to provide power to United States
  - Minimize forced outages with enhanced monitoring and diagnostics
- Small scale compared to conventional utility-scale coal power plants
  - 50-350 MW, minimize field construction costs
- Transformative of how coal technologies are designed and deployed
  - Coupled with energy storage, integrate with coal upgrading

Designing Coal FIRST Power Plants

Project Inception: 2019

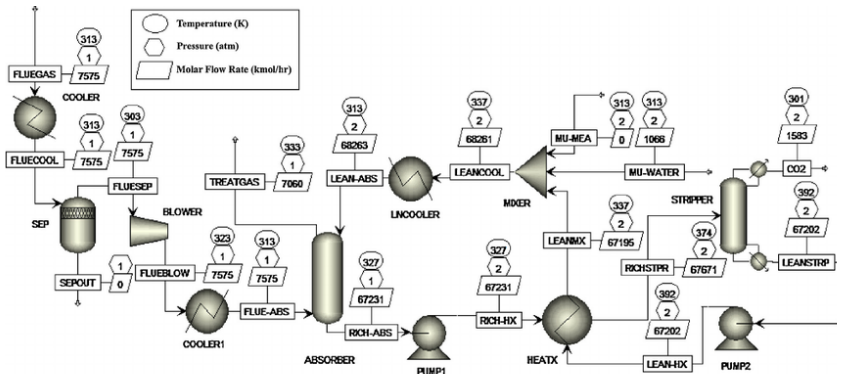
Flexible, Innovative, Resilient, Small and Transformational



- Develop robust conceptual design tools to identify the flexible design (< 350 MW)
- Develop reliable cost-estimating methodologies for new and existing candidate technologies
- Create advanced models for transformational technologies that enable optimal design and analysis
- Develop design targets that best integrate with the evolving needs of the electric grid
- Identify innovative materials using optimization that might help meet high performance metrics

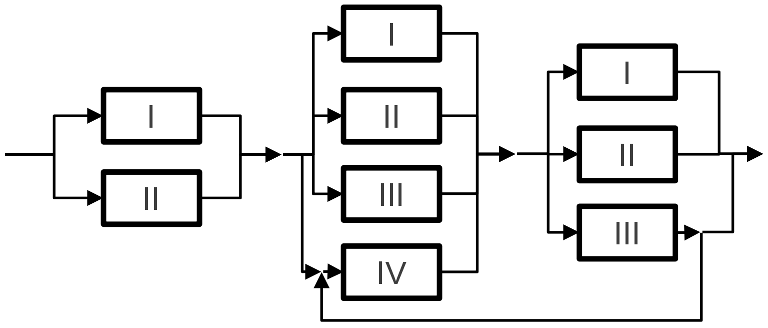
Process Design Studies – Status Quo

Techno-economic Studies

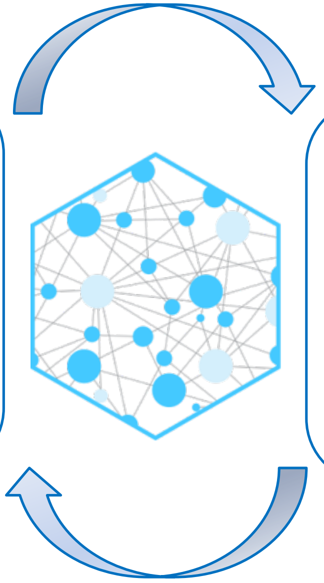


- Detailed steady-state models ✓
- Reasonable cost estimates ✓
- Not extensive, case by case analysis ✗
- Difficult to realize synergistic advantages ✗
- More a sensitivity study ✗

Conceptual Design Studies



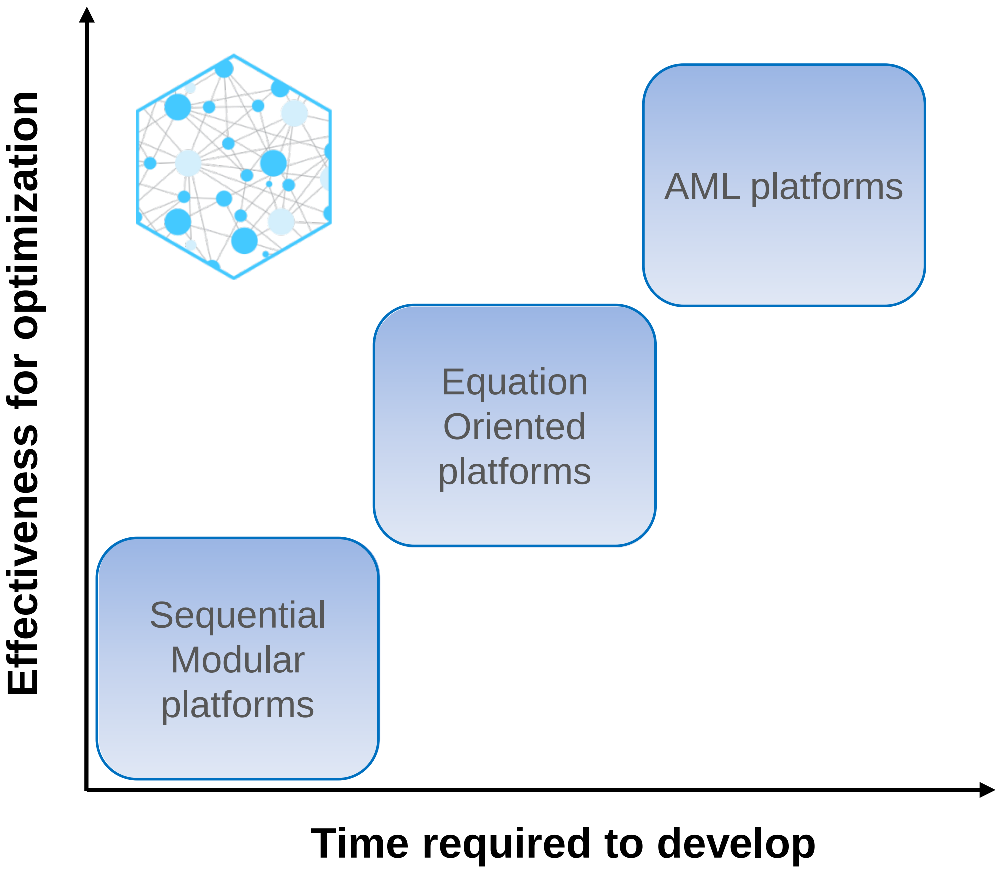
- Extensive search space ✓
- Realize synergies between processes ✓
- Simple input/output models ✗
- Performance prediction maybe erroneous ✗
- No commercial tool; mostly academic ✗



Update model

Validate design

The IDAES Approach



Effectiveness for optimization

AML platforms

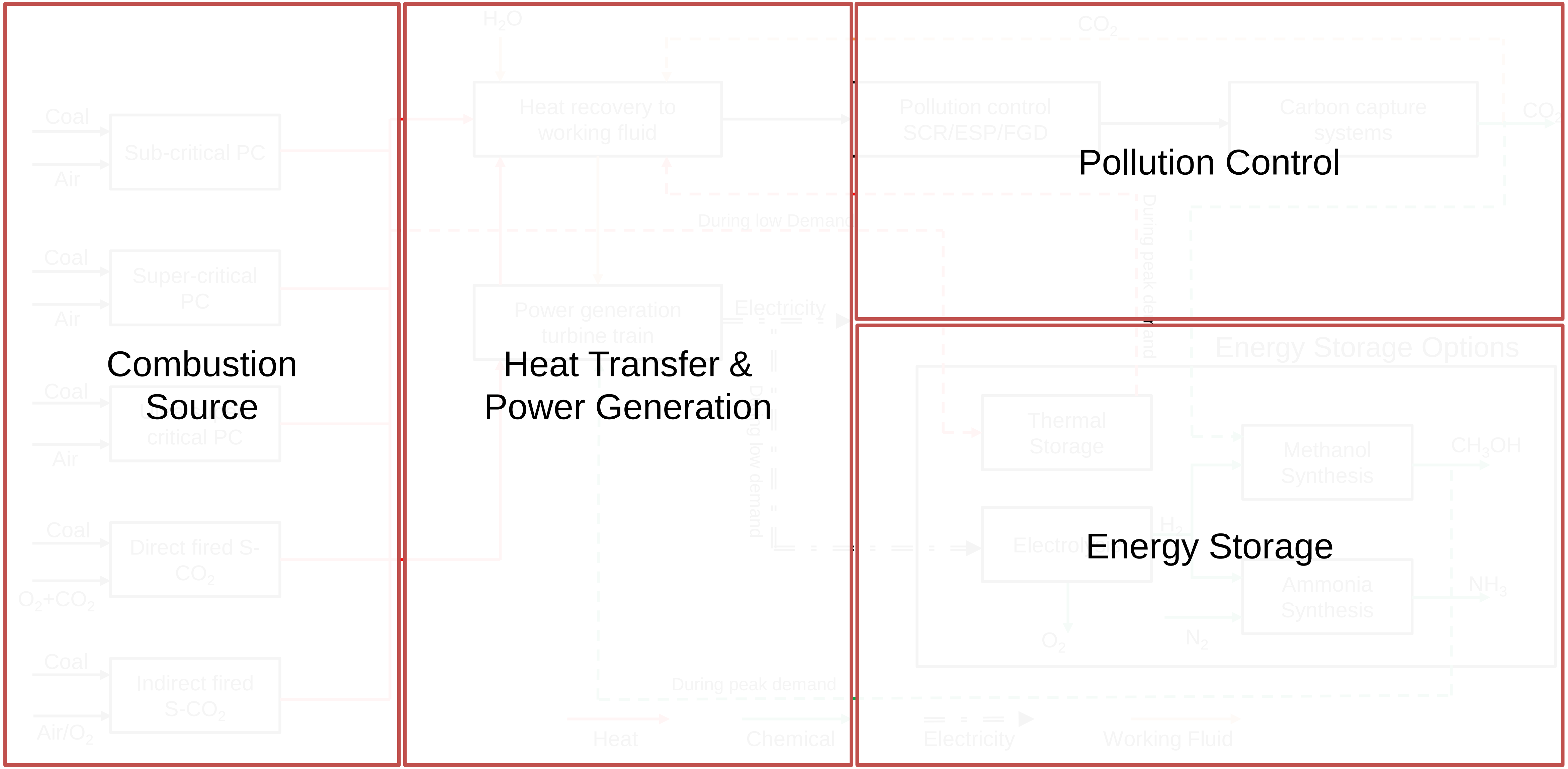
Equation Oriented platforms

Sequential Modular platforms

Time required to develop

Miller et al (2018), Computer Aided Chemical Engineering

Superstructure for Coal FIRST (Power Generation)


Combustion Source

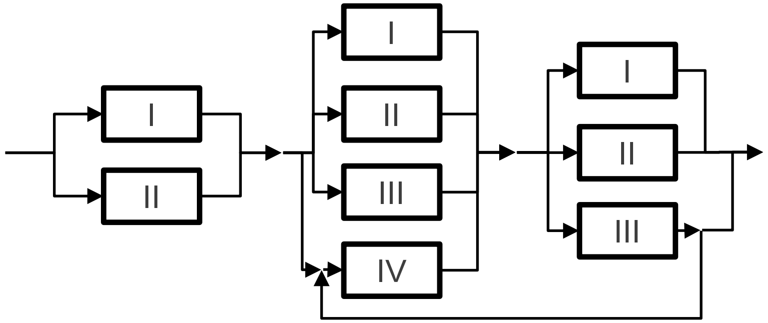
Heat Transfer & Power Generation

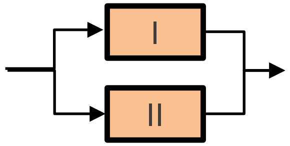
Pollution Control

Energy Storage

Conceptual Design Tools in IDAES

PyoSyn Framework in IDAES





Process 1

$$\begin{bmatrix} Process\ Equations \\ Costing\ correlation \\ + \\ Binary\ variable\ \{0,1\} \end{bmatrix}$$

or

Process 2

$$\begin{bmatrix} Process\ Equations \\ Costing\ correlation \\ + \\ Binary\ variable\ \{0,1\} \end{bmatrix}$$

9 disjunctions, 18 binary variables → 315 choices

$$\min z = f(x)$$ *Objective Function*

$$s.t.\ g(x) \le 0$$ *Global Constraints*

$$\bigvee_{i \in D_k} \begin{bmatrix} Y_{ki} \\ r_{ki}(x) \le 0 \end{bmatrix} \quad k \in K$$

$$\underline{\vee}_{i \in D_k} Y_{ki} \quad k \in K$$

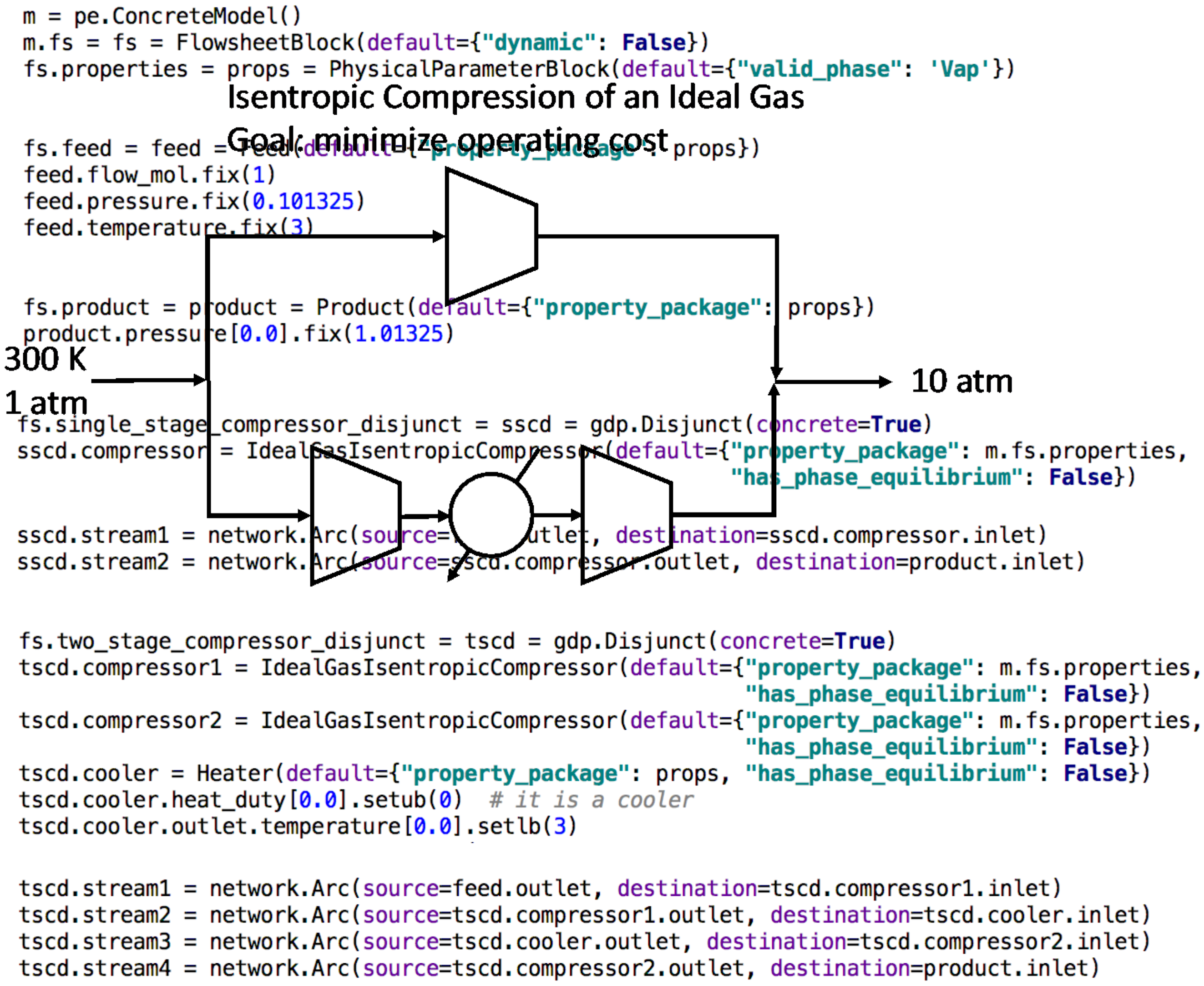
Disjunctions

$$\Omega(Y) = True$$ *Logic Propositions*

$$x \in \ \mathbb{R}^n Y_{ki} \in \{True, False\} \ \ k \in K, i \in D_k$$

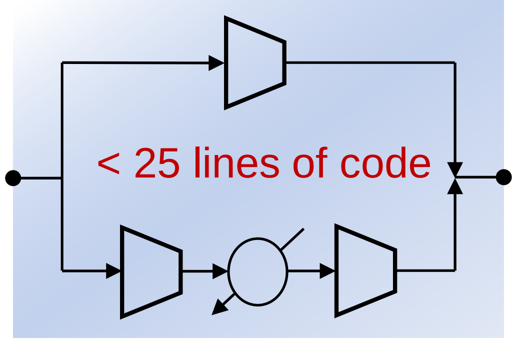
- Generalized Disjunctive Programming
- Automatically implement either-or logic
  - Less human **pre-processing**, fewer **modeling errors**

Implementation in IDAES – A Simple Example



```
m = pe.ConcreteModel()
m.fs = fs = FlowsheetBlock(default={"dynamic": False})
fs.properties = props = PhysicalParameterBlock(default={"valid_phase": 'Vap'})


fs.feed = feed = Feed(default={"property_package": props})
feed.flow_mol.fix(1)
feed.pressure.fix(0.101325)
feed.temperature.fix(3)


fs.product = product = Product(default={"property_package": props})
product.pressure[0.0].fix(1.01325)


fs.single_stage_compressor_disjunct = sscd = gdp.Disjunct(concrete=True)
sscd.compressor = IdealGasIsentropicCompressor(default={"property_package": m.fs.properties,
                                                       "has_phase_equilibrium": False})


sscd.stream1 = network.Arc(source=feed.outlet, destination=sscd.compressor.inlet)
sscd.stream2 = network.Arc(source=sscd.compressor.outlet, destination=product.inlet)


fs.two_stage_compressor_disjunct = tscd = gdp.Disjunct(concrete=True)
tscd.compressor1 = IdealGasIsentropicCompressor(default={"property_package": m.fs.properties,
                                                         "has_phase_equilibrium": False})
tscd.compressor2 = IdealGasIsentropicCompressor(default={"property_package": m.fs.properties,
                                                         "has_phase_equilibrium": False})
tscd.cooler = Heater(default={"property_package": props, "has_phase_equilibrium": False})
tscd.cooler.heat_duty[0.0].setub(0)  # it is a cooler
tscd.cooler.outlet.temperature[0.0].setlb(3)


tscd.stream1 = network.Arc(source=feed.outlet, destination=tscd.compressor1.inlet)
tscd.stream2 = network.Arc(source=tscd.compressor1.outlet, destination=tscd.cooler.inlet)
tscd.stream3 = network.Arc(source=tscd.cooler.outlet, destination=tscd.compressor2.inlet)
tscd.stream4 = network.Arc(source=tscd.compressor2.outlet, destination=product.inlet)
```

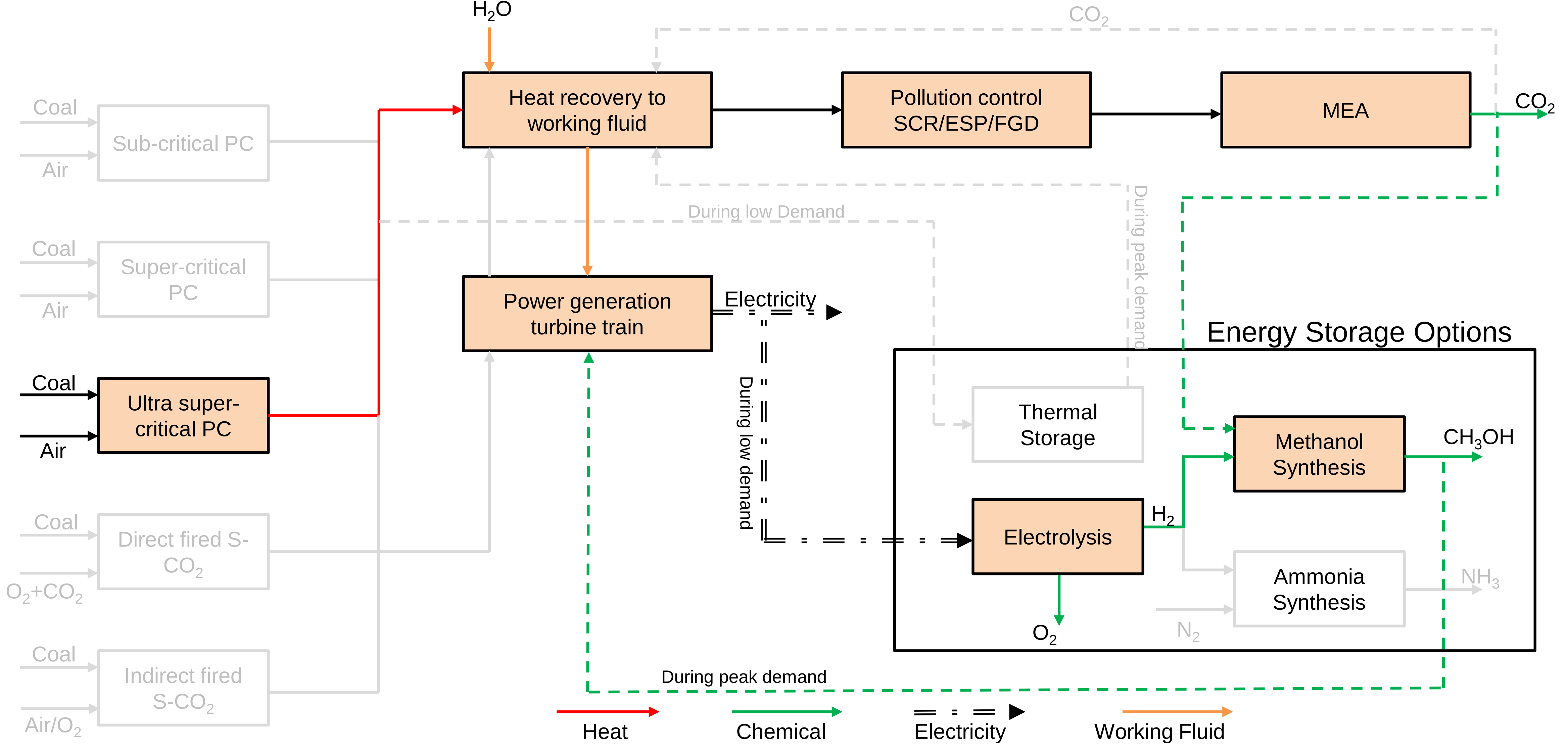
IDAES



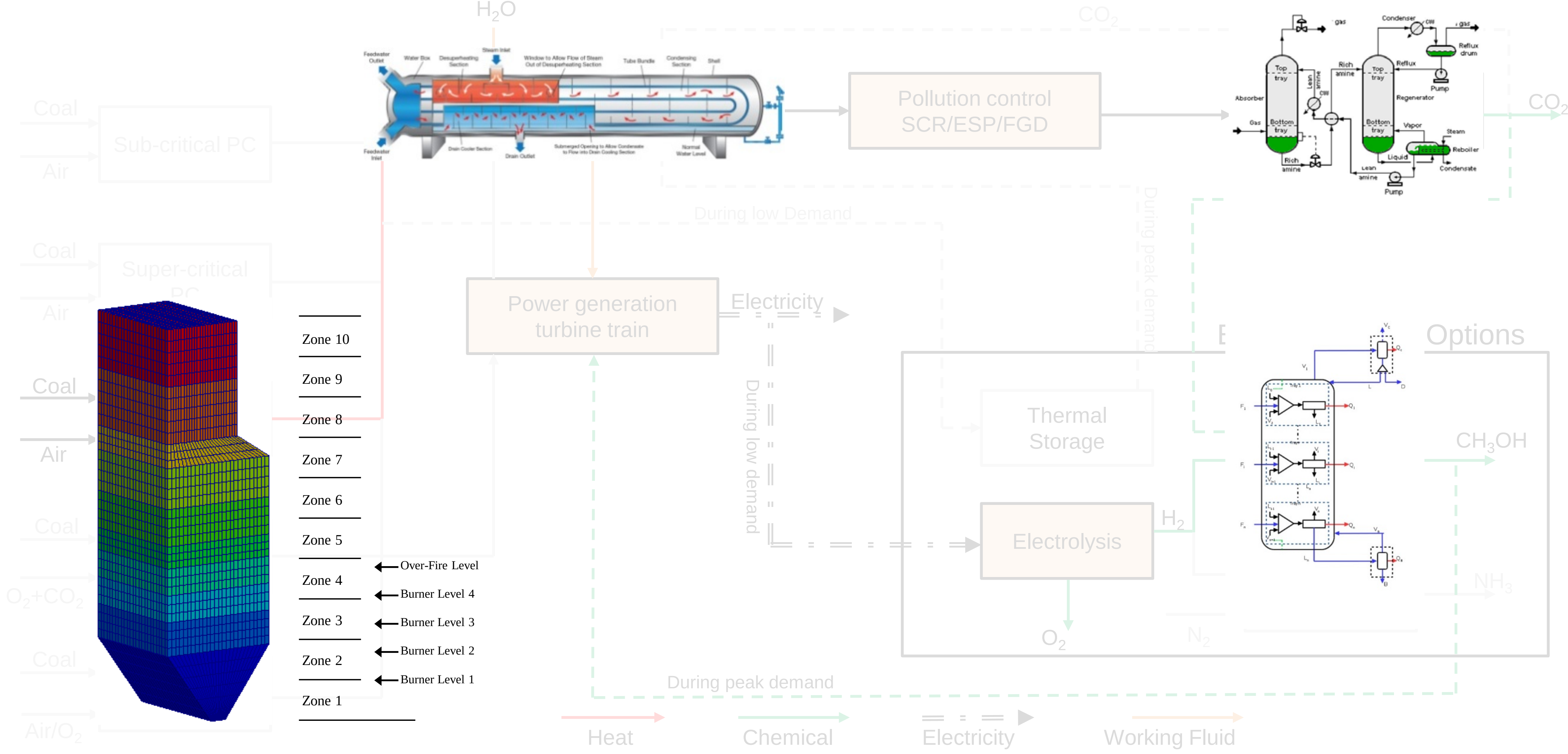
< 25 lines of code

SOLVE!

One Possible Design



Detailed Modeling

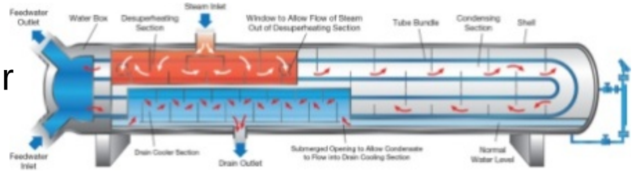


Advanced Modeling in IDAES

Detailed Modeling

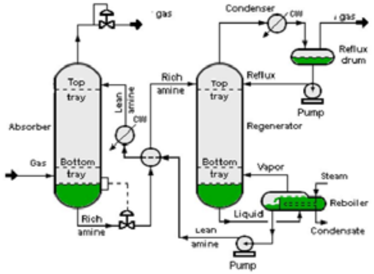
Unit Models

- Customized model library for power plant unit operations

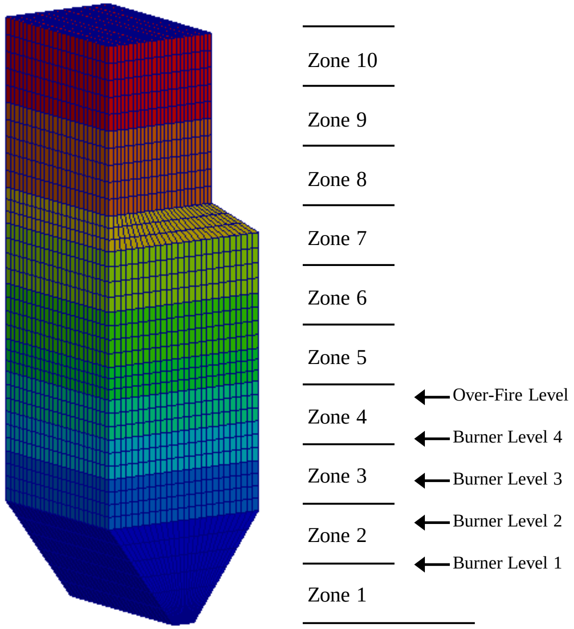


CO_2 Capture Model

- Liquid-gas contactor model

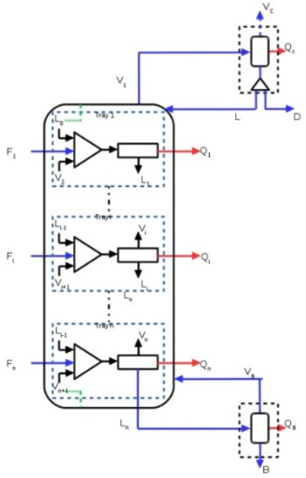


1D-3D Boiler Model



- Hybrid boiler model

Column Models

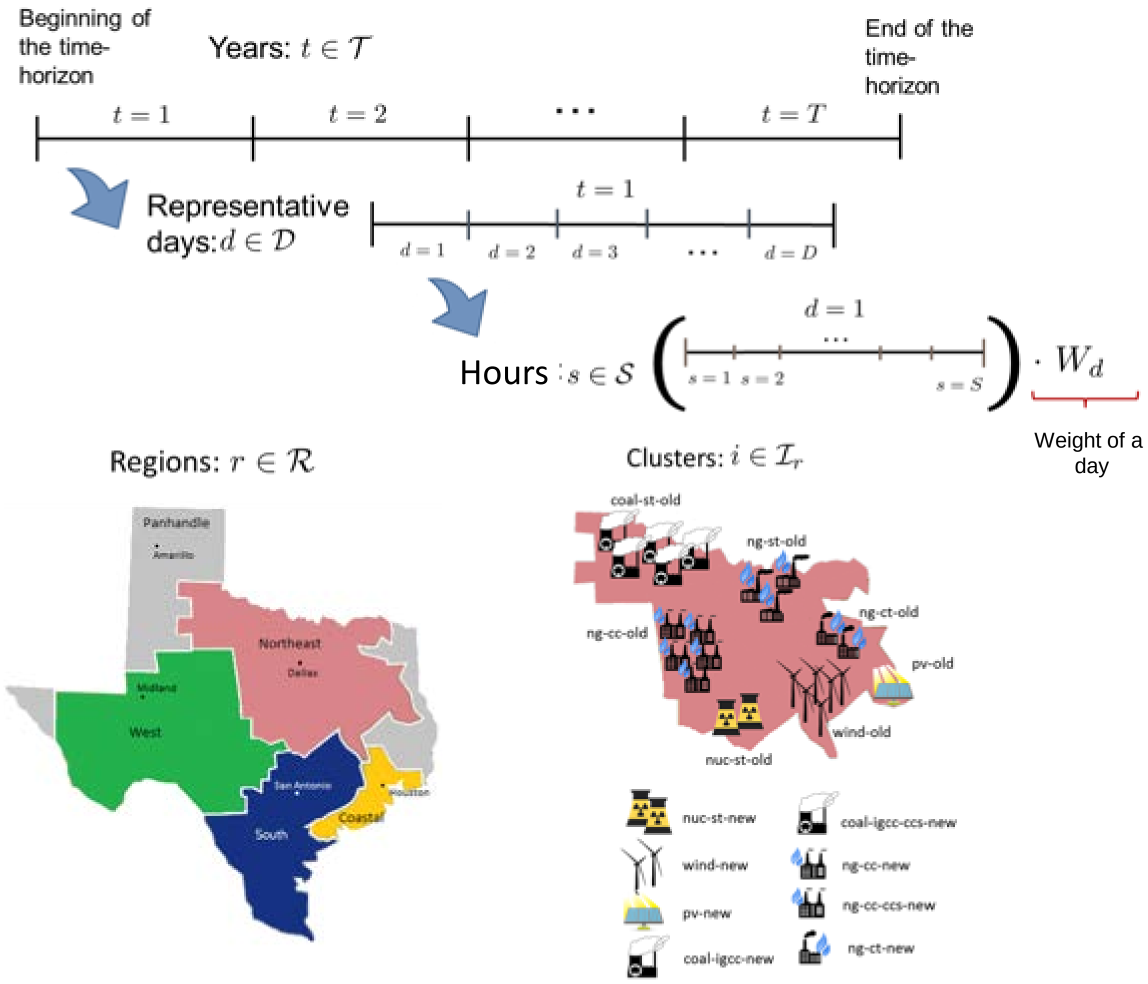


- MESH equations for each tray

Grid and Infrastructure Planning

Generation Expansion Planning

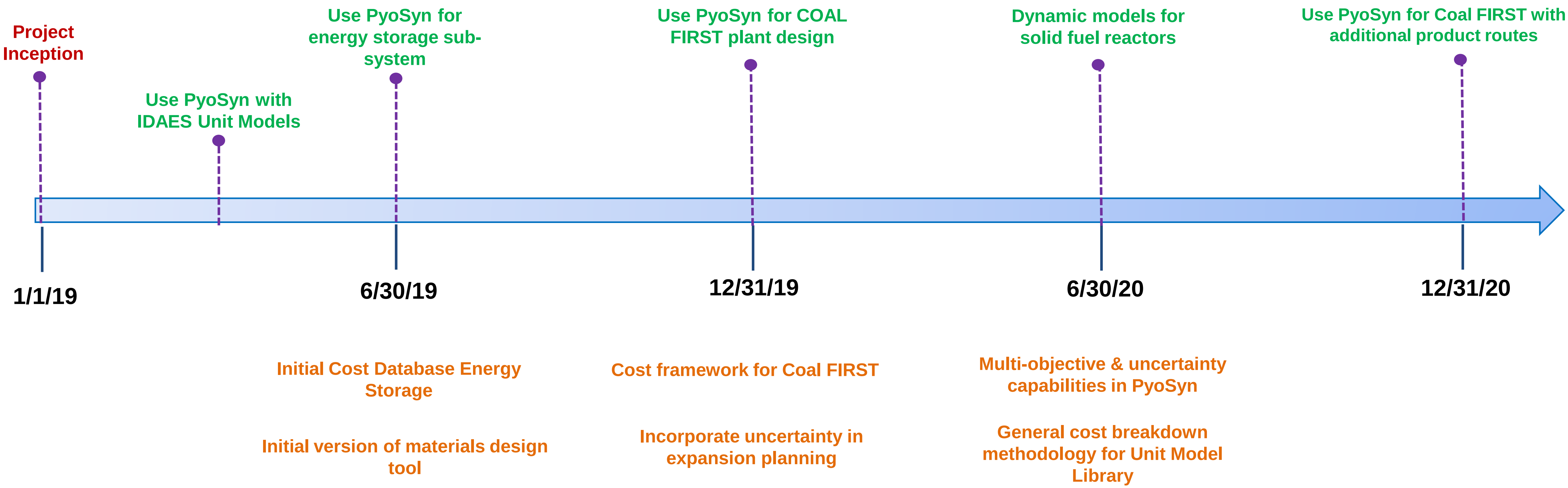
- Time scale approach:
  - Multi-year, days per year, hours per day
- Region and cluster representation
  - Area represented by a few zones
  - Potential locations are the midpoint in each zone
  - Clustering of generators
- Transmission representation
  - Flow in each line is determined by the energy balance between each region *r*



Project Milestones & Timeline

APPLICATIONS

TOOLSET



Project Inception

Use PyoSyn with IDAES Unit Models

Use PyoSyn for energy storage sub-system

Use PyoSyn for COAL FIRST plant design

Dynamic models for solid fuel reactors

Use PyoSyn for Coal FIRST with additional product routes

1/1/19

6/30/19

12/31/19

6/30/20

12/31/20

Initial Cost Database Energy Storage

Initial version of materials design tool

Cost framework for Coal FIRST

Incorporate uncertainty in expansion planning

Multi-objective & uncertainty capabilities in PyoSyn

General cost breakdown methodology for Unit Model Library

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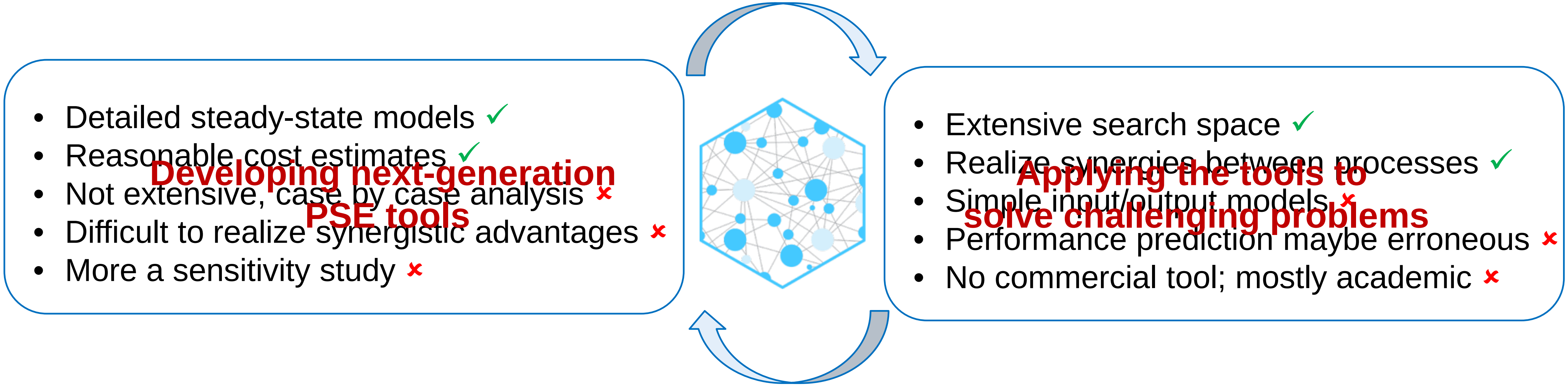
Conclusions

- Coal FIRST plant design
  - Large and complex problem
  - Multi-scale (particle level to grid interactions)
  - Explore value addition for coal plants (power +)



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Developing next-generation PSE tools

- Extensive search space ✓
- Realize synergies between processes ✓
- Simple input/output models ✗
- Performance prediction maybe erroneous ✗
- No commercial tool; mostly academic ✗

Applying the tools to solve challenging problems

Acknowledgments

www.idaes.org

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- WVU: Debangsu Bhattacharyya, Paul Akula, Anca Ostace, Quang-Minh Le
- ND: Alexander Dowling, Xian Gao

Appendix

Modular Coal-fired Power Plants: Cost of Electricity

Costing Methodology

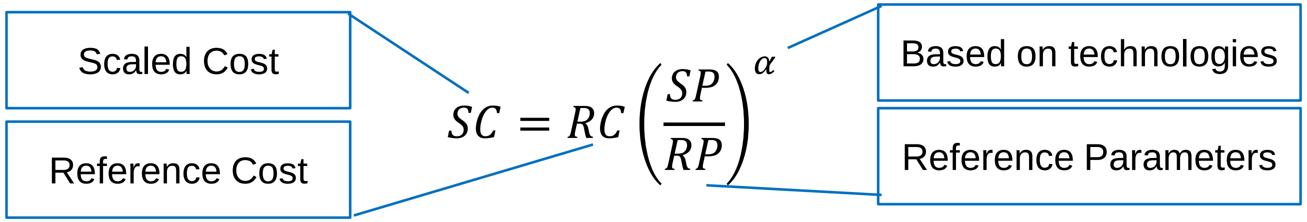
- **Investment cost**
- **Operating cost**
  - Fixed: labor, maintenance, others
  - Variable: utilities “coolant & steam,” waste water, others
- **Net Power**
- **Storage Technologies**

$$COE = \frac{(Investment\ + Operating_{fix} + Operating_{var})}{(Net\ Power)}$$

Quality Guidelines for Energy System Studies: Performing a Techno-economic Analysis for Power Generation Plants (DOE/NETL-2015/1726)

Product and Process Design Principles Synthesis (Seider et al., 2009) Purchase cost correlations

Modular Power Plants (250 MW to 500 MW): Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology (DOE/NETL-2013/341)



$$SC = RC\left(\frac{SP}{RP}\right)^{\alpha}$$

α, RP, RC, SP

- Subcritical, Supercritical, and ultra-supercritical
- air-fired and oxy-fired
- with and without CO_2 capture
- Ilinois No. 6 coal, PRB and ND Lignite coals
- IGCC
- Large Data base (vendor quotes)